Measurement of Strain in Al-Cu Interconnect Lines with X-ray Microdiffraction

The interconnect lines in integrated circuits, which are only a few microns wide, suffer from reliability problems due to the often coupled electromigration and mechanical stress phenomena. This study uses x-ray microdiffraction from the interconnects to reveal the details of the microscopic stress and its origin.

The semiconductor industry owes much of its current success to the reliability of the products it delivers. Consumers expect their computers and other electronic devices to perform reliably for many years. In many fields of applications such as medicine, defense, and finance, reliability is not just a convenience but an essential requirement. Making increasingly reliable devices as they become more and more complex is an extremely challenging task.

Modern integrated circuits use tiny metal lines to interconnect thousands to millions of components on a semiconductor chip. Aluminum, alloyed with small amounts of copper and silicon, has been the material of choice for many years. Even though the technology to realize pure Cu interconnects was recently developed and begun to be used in production, Al is expected to keep its dominant status for some time.

Aluminum interconnect lines suffer from reliability problems due to the often coupled electromigration and mechanical stress phenomena. In the current production technology, Al is deposited as a uniform film over a substrate and later patterned with lithographic techniques to obtain the desired interconnect structures. These Al films usually have tensile stress after manufacturing processes at elevated temperatures due to the differential contraction of Al and the surrounding materials. This residual tensile stress was observed to sever the lines by inducing large voids. At the other extreme, compressive stress can cause growth of hillocks on the lines that may damage the surrounding circuitry.

Electromigration—the movement of conductor atoms due to the force exerted by an electrical current—is another notorious process that damages interconnects. It creates circuit failures by forming fatal voids or hillocks. As the transport of material due to electromigration proceeds in a metal line, material is accumulated near the anode end and depleted near the cathode end. This process creates a stress gradient along the line, which is confined by the substrate and the dielectric passivation layers. Then the atoms start to feel two opposing forces, one due to the electron wind and the other due to the stress gradient. Under certain conditions, these two forces can completely balance each other and halt the atomic flow. Under this balance condition, a constant stress gradient exists along the line. In a pioneering article, Blech and Sello showed that there is a critical interconnect length—electric current density product below which this balance is achieved and no electromigration damage occurs [1]. This phenomenon significantly affects the resistance of interconnect structures to electromigration damage.

Experimental verification of this interplay between electromigration and stress-induced flows has proved difficult mainly because of the difficulty of stress measurement with micron- or submicron-scale spatial resolution. In x-ray diffraction measurement of stress, the sampled area with traditional x-ray sources is too large to allow measurement of stress distribution with necessary spatial resolution. Development of extremely high brightness synchrotron radiation sources such as the Advance Photon

Source (APS) and advances in x-ray optics such as the development of Fresnel zone plates (FZP) for hard x-rays has opened new possibilities in this area. There is increasing interest in the community on this problem [2,3].

We conducted experiments on the 2-ID-D undulator beamline of APS using FZPs as focusing elements to measure strain distribution on Al-Cu interconnects [4]. The zone plates were manufactured at the Center for NanoTechnology (CNTech) by x-ray replication and Au electroplating techniques [5]. The experimental station is equipped with a goniometer, a scanning sample stage with submicron resolution, an energy-dispersive Ge x-ray detector, and an x-ray CCD camera along with other optical alignment instruments. The interconnect line sample was a single 1.6-µm-wide, 270-µm-long Al-2% Cu line passivated with a 700-nm-thick SiO_2 film. Another sample with a thick Al-Cu blanket film was used as a reference for strain measurement.

Figure 1 shows a schematic of the experimental setup. The CCD detector was placed to accept both (111) and (200) reflections from the Al lattice

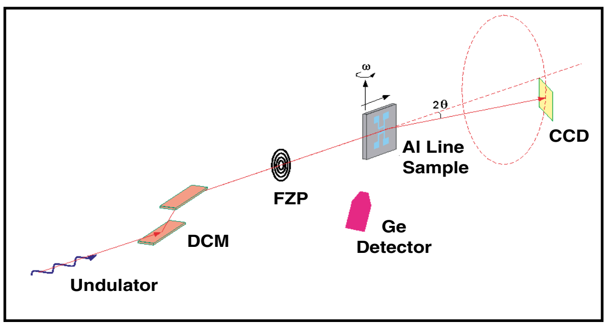

FIG. 1. Schematic view of the setup for microdiffraction experiments. X-rays produced by an undulator in the storage ring are monochromatized by a double-crystal monchromator (DCM) and focused on the thin Al-Cu film sample by a FZP. The patterned Al-Cu line runs perpendicular to the horizontal plane.

in an approximately symmetric reflection geometry. The interconnect line was placed in the focused beam by following the Cu Kα fluorescent emission, which was detected by the energy-dispersive x-ray detector. A sample CCD image obtained from the thick blanket film sample showing (111) and (200) diffraction spots is shown in Fig. 2.

The line sample was placed in the focused x-ray beam, and microdiffraction images were obtained from a 100-µm-long section of the line at regular intervals. The sample was subsequently

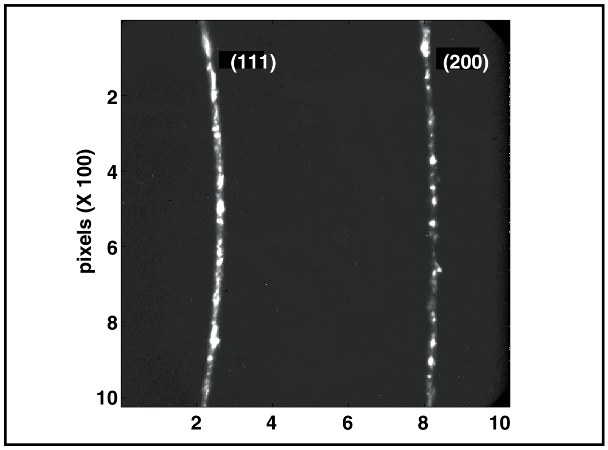

FIG. 2. Microdiffraction pattern from a thick blanket Al-Cu film. The image resembles a powder diffraction pattern due to the large number of contributing grains.

removed from the goniometer stage and placed in an oven for electromigration stressing. After the electromigration test, the same 100-µm-long section of the line was inspected with the microdiffraction technique for changes in the strain state.

The CCD microdiffraction images obtained from points on the Al-Cu line contained several (111) and (200) diffraction spots each. The positions of these spots are related to the strain in the diffracting crystal lattice through the familiar Bragg equation. Figure 3 shows the variation of strain along the line as measured from both (111) and (200) reflections. Note that these measurements are from two distinct set of grains [i.e., those with (111) and (200) planes parallel to the substrate surface, respectively]. Statistical tests on the data confirmed that the strain profile "before electromigration" is determined largely by grain-to-grain variation. However, the strain values "after electromigration" showed strong dependence on position along the line. This can easily be noticed in Fig. 3(b) where the data from (111) and (200) grains seem to follow each other fairly well. However, we also observe a higher strain variation in the (200) strain profile coupled with more pronounced extremes.

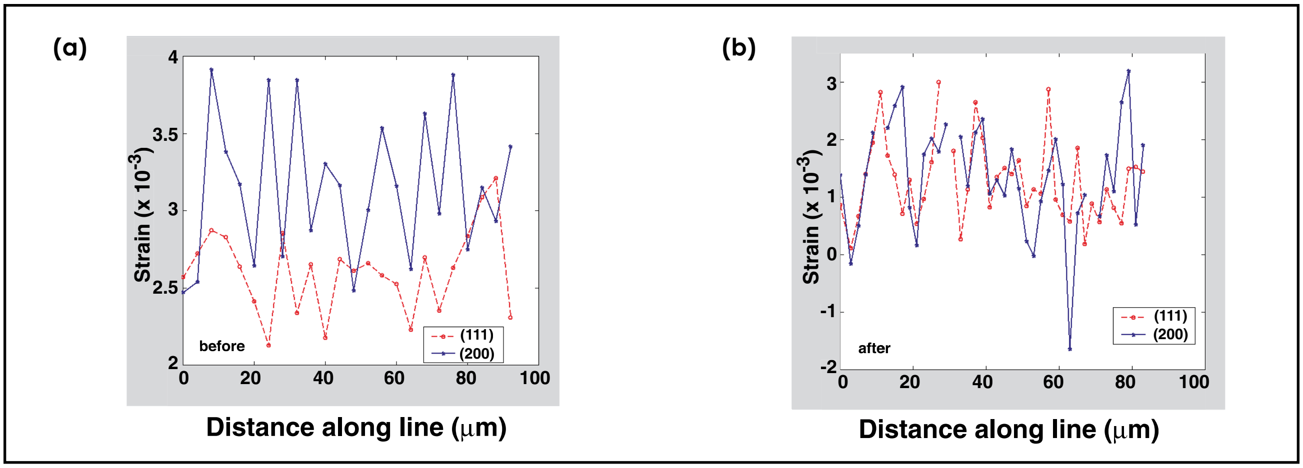

FIG. 3. Strain profile along line (a) before and (b) after electromigration stressing. Dashed and solid lines show the measurement from (111) and (200) spots, respectively.

The size and shape of a spot reveal additional information about the diffracting grain. In particular, its width in the dispersion direction depends on the strain variation in the grain, among other factors.

Our data showed that the diffraction spots grew in width after the electromigration test, indicating an increase in intragrain strain variation. This increase was significantly higher for the (200) orientation grains. It is well known that Al lines with higher (111) crystallographic texture are more resistant to electromigration damage. In fact, our results show different strain behavior for (111) and (200) grains, with less variation and overall milder behavior among the (111) grains. On the basis of our observations and assuming a threshold stress value for line damage, we can infer that lines with higher (111) texture are less likely to attain this threshold value and consequently less likely to sustain damage.

We note the significant absence of a long-range strain gradient opposing the electromigration flow. This may be attributed to the relaxation of stress during the time that elapsed between the test and the subsequent x-ray measurement. *In situ* tests should shed light on this point.

In this study, we used the strain variation in the normal direction as an indicator of the more general strain state in the sample. A complete determination of the three-dimensional strain state requires measurements in six different directions to account for all normal and shear components. We are planning to expand our studies to include *in situ* characterization as well as strain measurements in more directions.

Principal publication: "Measurement of Strains in Al-Cu Interconnect Lines with X-ray Microdiffraction," J. Appl. Phys **86**, 884 (1999).

References

[1] I.A. Blech, and H. Sello, Physics of Failures in Electronics USAF-RADC Series, **5**, 496 (1966).

[2] P.-C. Wang, G.S. Cargill, I.C. Noyan, and C.-K. Hu, Appl. Phys. Lett. **72**, 1296 (1998).

[3] H. Zolak, Y. Vladimirsky, F. Cerrina, B. Lai, W. Yun, Z. Cai, P. Ilinski, D. Legnini, and W. Rodrigues, J. Appl. Phys. **86**, 884 (1999).

[4] W. Yun, B. Lai, D. Shu, A. Khounsary, Z. Cai, J. Barraza and D. Legnini, Rev. Sci. Instrum. **67** (9), CD-ROM (1996).

[5] A. Krasnoperova, J. Xiao, F. Cerrina, E. DiFabrizio, L.Luciani, M. Figliomeni, W. Yun, B. Lai, and E. Gluskin, J.Vac. Sci. Technol. B **11**, 2588 (1993).

H. Solak,[1] Y. Vladimirsky,[1] F. Cerrina,[1] B. Lai,[2] W. Yun,[2] Z. Cai,[2] P. Ilinski,[2] D. Legnini,[2] W. Rodrigues[2]

[1] *Department of Electrical and Computer Engineering, University of Wisconsin-Madison, WI, U.S.A.*

[2] *Argonne National Laboratory, Argonne, IL, U.S.A.*